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Software Vulnerabilities

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Software Vulnerabilities

Program flaws can turn into exploitable vulnerabilities

Securing user-space applications is equally critical as securing the OS

- May run with superuser privileges: system daemons, setuid programs, anything launched by the root account, …
- Non-privileged applications may be a stepping stone to full system compromise ➔ privilege escalation attacks
- The OS is software too

Full system compromise may not even be needed (!)

- User data is handled by applications ➔ compromising an application may be enough
- Browsers, password managers, messaging apps, …

Types of Software Vulnerabilities

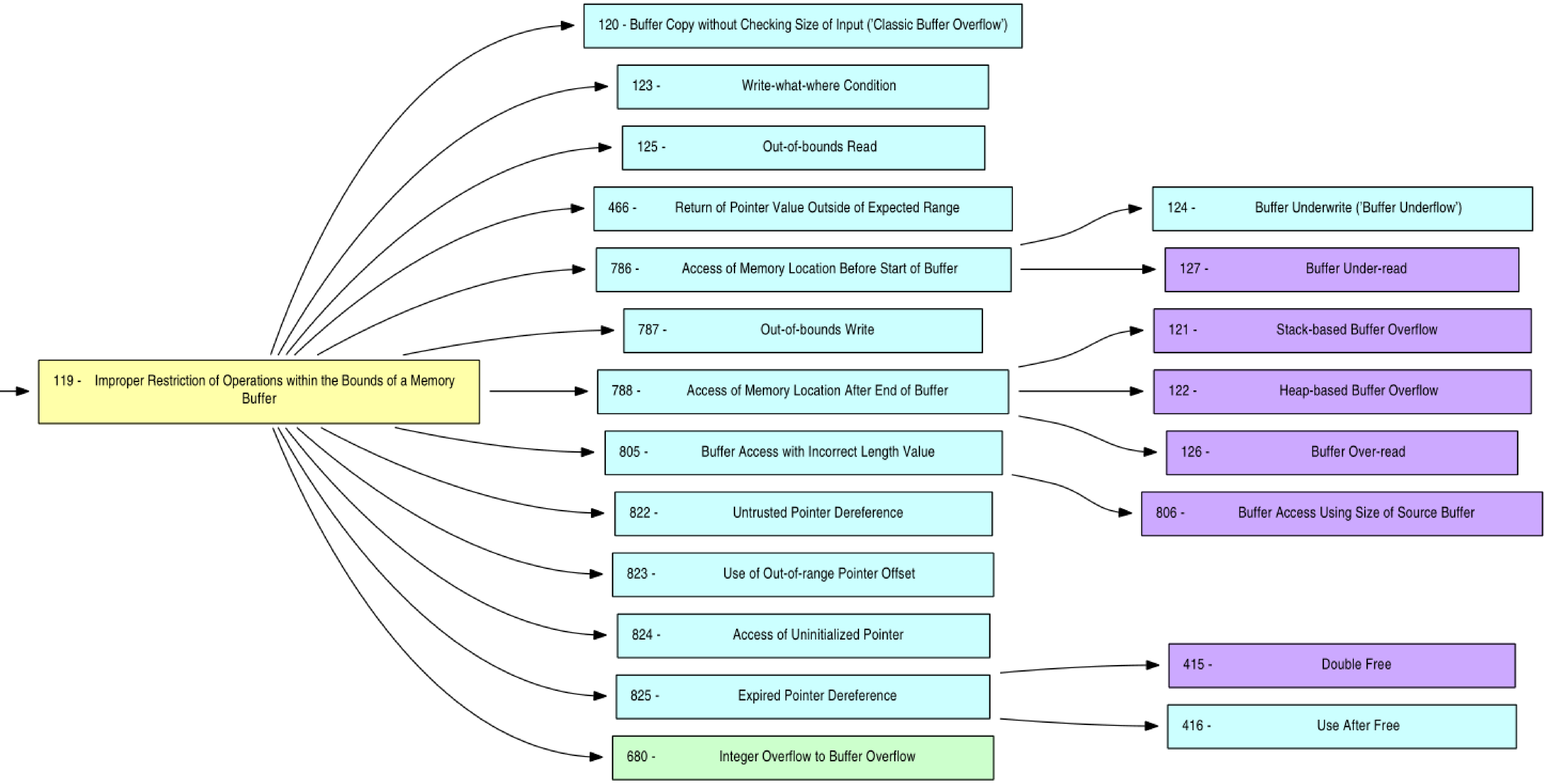
Vast number of different types of programming flaws, weaknesses, omissions, and other oversights

- Many different corresponding exploitation techniques

Classifications according to different aspects include:

- Type of bug
- Exploitation strategy
- SDL phase
- Programming language
- System layer

Example: MITRE's Common Weakness Enumeration (CWE) classification


120 - Buffer Copy without Checking Size of Input ('Classic Buffer Overflow')
123 - Write-what-where Condition
125 - Out-of-bounds Read
466 - Return of Pointer Value Outside of Expected Range
786 - Access of Memory Location Before Start of Buffer
787 - Out-of-bounds Write
119 - Improper Restriction of Operations within the Bounds of a Memory Buffer
788 - Access of Memory Location After End of Buffer
805 - Buffer Access with Incorrect Length Value
822 - Untrusted Pointer Dereference
823 - Use of Out-of-range Pointer Offset
824 - Access of Uninitialized Pointer
825 - Expired Pointer Dereference
680 - Integer Overflow to Buffer Overflow
124 - Buffer Underwrite ('Buffer Underflow')
127 - Buffer Under-read
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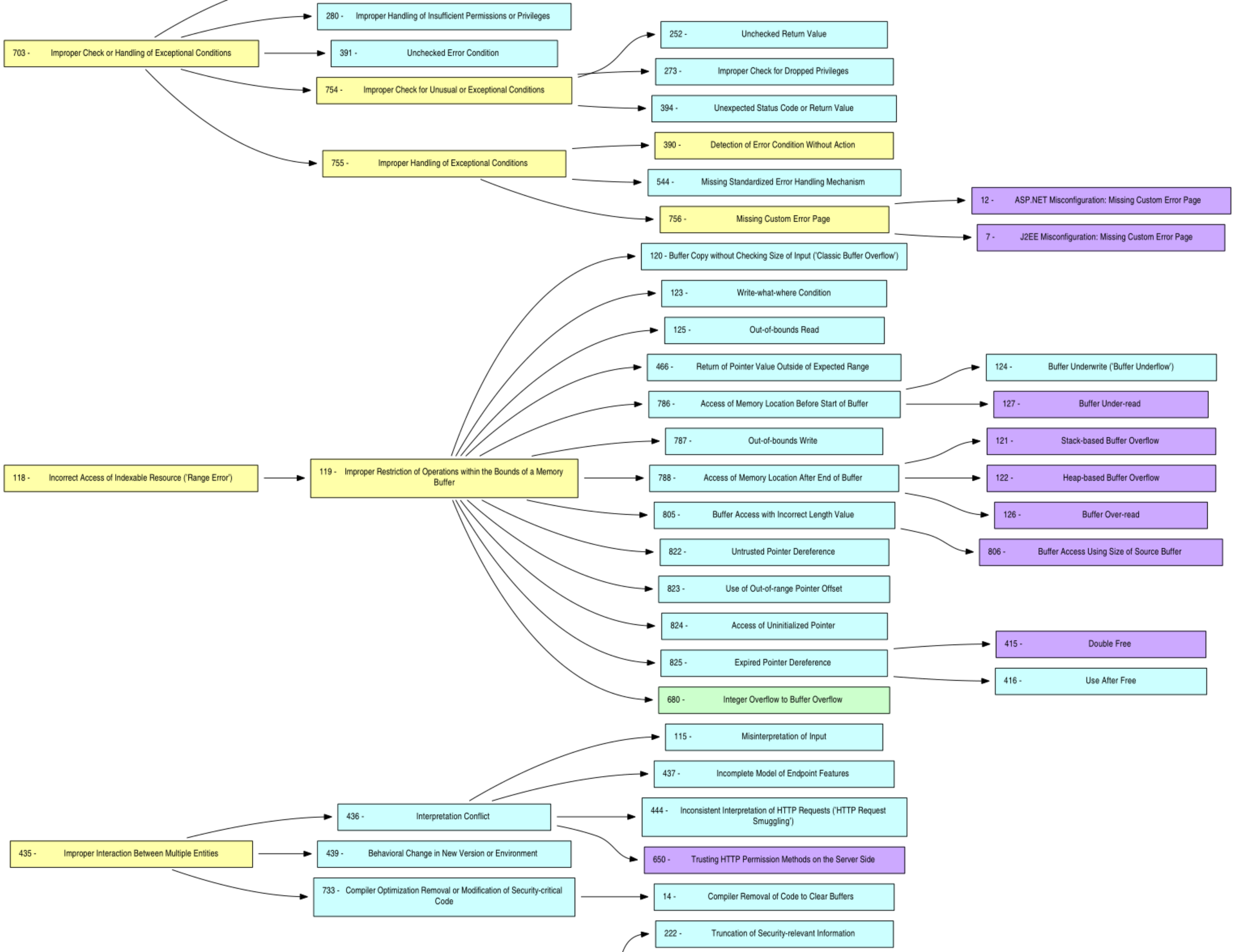
122 - Heap-based Buffer Overflow
126 - Buffer Over-read
806 - Buffer Access Using Size of Source Buffer
415 - Double Free
416 - Use After Free


280 - Improper Handling of Insufficient Permissions or Privileges
703 - Improper Check or Handling of Exceptional Conditions
391 - Unchecked Error Condition
252 - Unchecked Return Value
273 - Improper Check for Dropped Privileges
754 - Improper Check for Unusual or Exceptional Conditions
394 - Unexpected Status Code or Return Value
390 - Detection of Error Condition Without Action
755 - Improper Handling of Exceptional Conditions
544 - Missing Standardized Error Handling Mechanism
12 - ASP.NET Misconfiguration: Missing Custom Error Page
756 - Missing Custom Error Page
7 - J2EE Misconfiguration: Missing Custom Error Page
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121 - Stack-based Buffer Overflow
118 - Incorrect Access of Indexable Resource ('Range Error')
119 - Improper Restriction of Operations within the Bounds of a Memory Buffer
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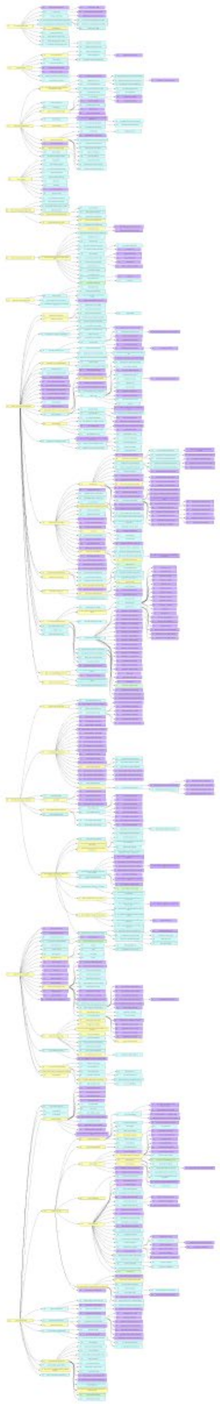
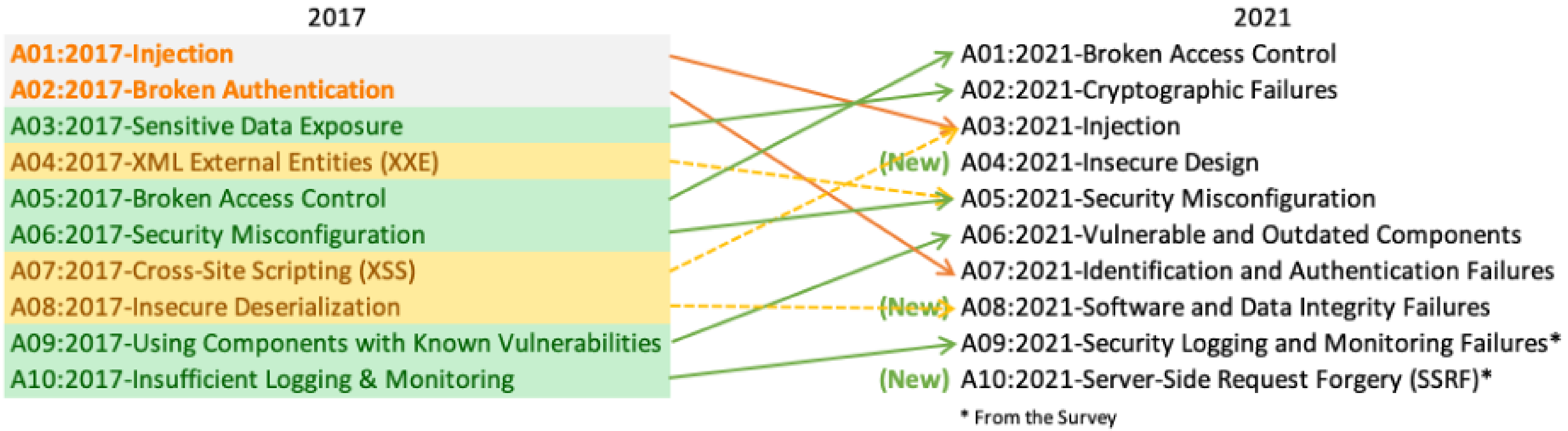
416 - Use After Free
680 - Integer Overflow to Buffer Overflow
115 - Misinterpretation of Input
437 - Incomplete Model of Endpoint Features
436 - Interpretation Conflict
444 - Inconsistent Interpretation of HTTP Requests ('HTTP Request Smuggling')
435 - Improper Interaction Between Multiple Entities
439 - Behavioral Change in New Version or Environment
650 - Trusting HTTP Permission Methods on the Server Side
733 - Compiler Optimization Removal or Modification of Security-critical Code
14 - Compiler Removal of Code to Clear Buffers
222 - Truncation of Security-relevant Information



Another example: OWASP Top 10

“The ten most critical web application security risks”



https://owasp.org/www-project-top-ten/

Some Basic Types of Software Vulnerabilities

Memory corruption: stack/heap buffer overflow, dangling pointers, …

Arithmetic errors: arithmetic overflow, signedness, array indexing, …

Race conditions: synchronization issues, TOCTTOU bugs, …

Unvalidated input: format strings, SQL injection, command injection, …

Confused deputy: CSRF, clickjacking, …

Side channels: timing, power, temperature, …

Program logic/design/protocol flaws: wrong/missing checks, typos, …

Arithmetic Overflow

Finite number of bits to represent integers

Let's assume a 32-bit system

Integers are expressed in *two's complement* notation

Signed integers

Positive numbers: `0x00000000 – 0x7fffffff` 0 to $2^{31}-1$

Negative numbers: `0x80000000 – 0xffffffff` $-(2^{31})$ to -1

Unsigned integers

`0x00000000 – 0xffffffff` 0 to $2^{32}-1$

Both can *overflow* or *underflow*

“Only the first five clients can connect”

```
unsigned int connections = 0;
...
/* new connection attempt */
...
connections++;
if (connections < 5) {
  grant_access();
}
else {
  deny_access();
}
```

How can an attacker connect even if there are already five established connections?

“Only the first 5 clients can connect”

```
unsigned int connections = 0;
...
/* new connection attempt */
...
if (connections < 5) {
  connections++;
}
if (connections < 5) {
  grant_access();
}
else {
  deny_access();
}
```

Upper bound of five connections is enforced

Memory-related Errors

Very broad class of *undefined memory access* vulnerabilities

- One of the most important and widely exploited types of vulnerabilities
- *Buffer overflow, null pointer dereference, use after free, uninitialized memory use, …*

In contrast to *memory safe* languages, C and C++ do not safeguard memory against illegal accesses

- Under unexpected conditions, attackers may be able to *read* from or *write* to arbitrary memory locations

Lower-level languages ➔ performance

- Operating systems, core services, desktop applications, embedded systems, and many other programs are still written in C/C++
- Promising recent progress on low-overhead memory-safe languages (e.g., Rust, Go)

Buffer Overflow

C and C++ do not provide any automatic bounds checking capability for allocated chunks of memory

- Arrays: can be indexed past the first (underflow) or last (overflow) item
- Pointers: can point outside the allocated object

Care must be taken when reading/writing user-supplied or user-derived data from/to memory

- More data than expected may be supplied ➔ overflow
- The program should perform explicit bounds checks

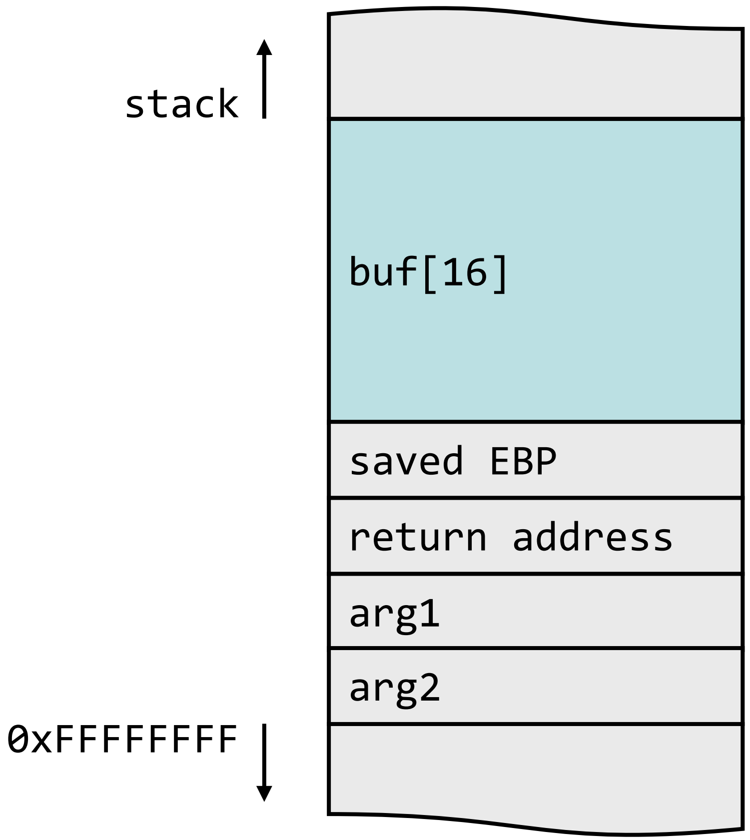
An attacker can intentionally overflow the buffer and access out-of-bounds memory

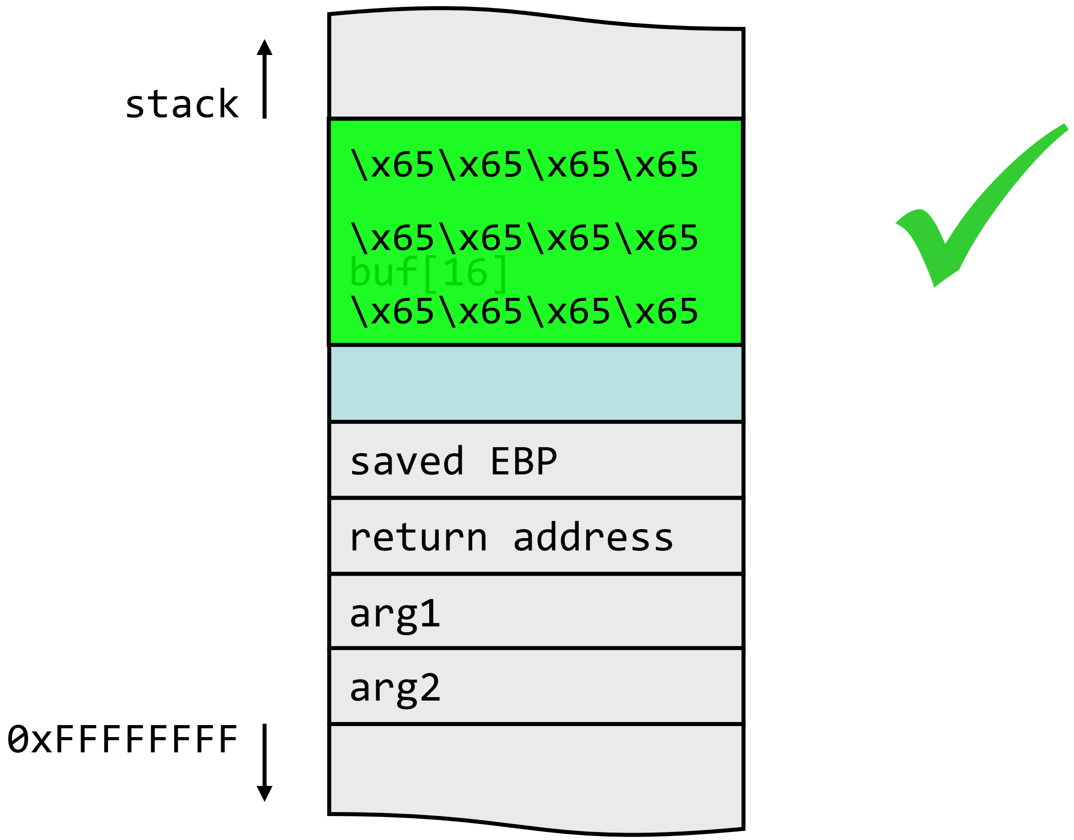
- Modify critical control or program data (overwrite)
- Leak sensitive information (overread)

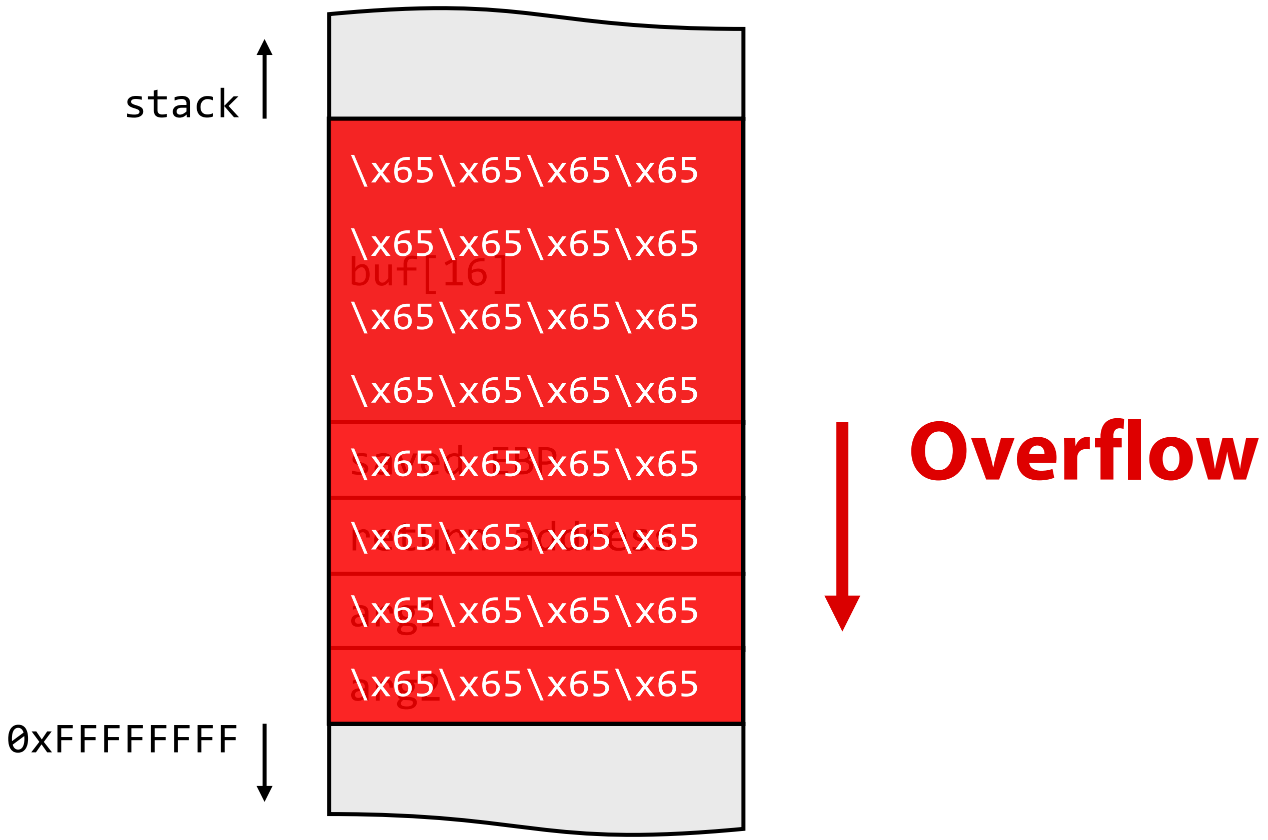
Simple overflow example: unbounded string copy

```
int main(int argc, char *argv[]) {
  char buf[16];
  strcpy(buf, argv[1]);
  printf("%s\n", buf);
  return 0;
}

$ ./overflow AAAAAAAAAAAA
AAAAAAAAAAAAAAAA
$ ./overflow AAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAA
Segmentation fault (core dumped)
```


stack
buf[16]
saved EBP
return address
arg1
arg2
0xFFFFFFFF


stack
\x65\x65\x65\x65
\x65\x65\x65\x65
buf[16]
\x65\x65\x65\x65
saved EBP
return address
arg1
arg2
0xFFFFFFFF


stack
\x65\x65\x65\x65
\x65\x65\x65\x65
buf[16]
\x65\x65\x65\x65
\x65\x65\x65\x65
\x65\x65\x65\x65
\x65\x65\x65\x65
\x65\x65\x65\x65
\x65\x65\x65\x65
0xFFFFFFFF
Overflow

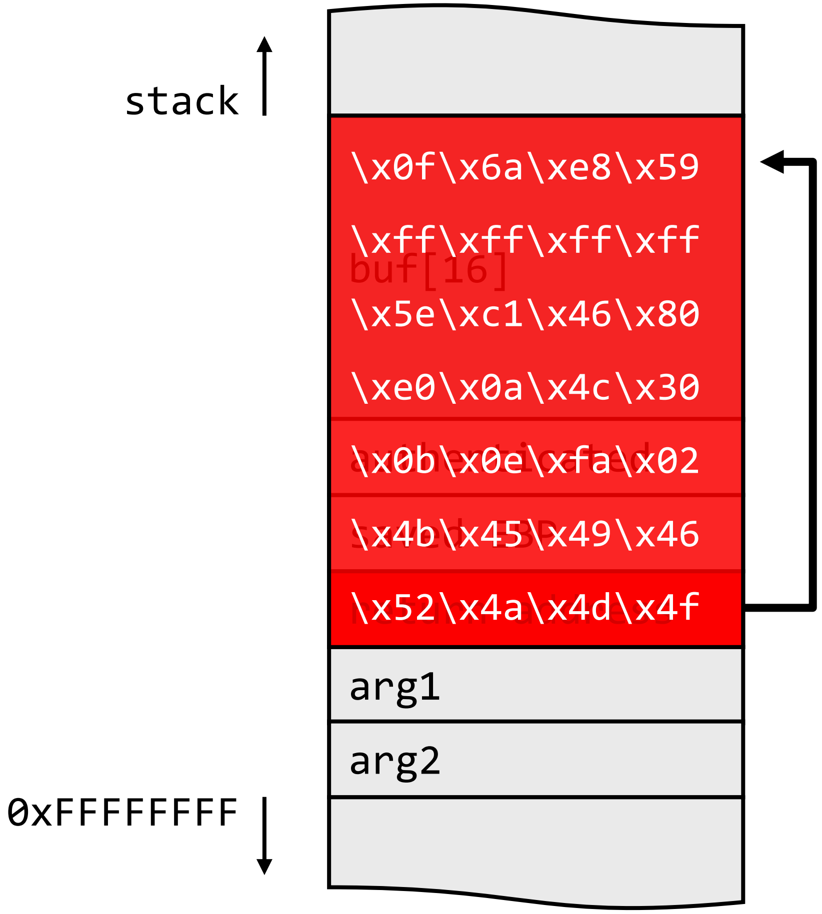
Safer way

```c
#define BUF_SIZE 16

int main(int argc, char *argv[]) {
  char buf[BUF_SIZE];
  strncpy(buf, argv[1], BUF_SIZE);
  printf("%s\n", buf);
  return 0;
}
```

Excplicit bounds check:
`strncopy` will never write more than BUF_SIZE bytes into buf

What can the attacker do? ***Overwrite control data***



Arbitrary code execution

spawn shell

listen for connections

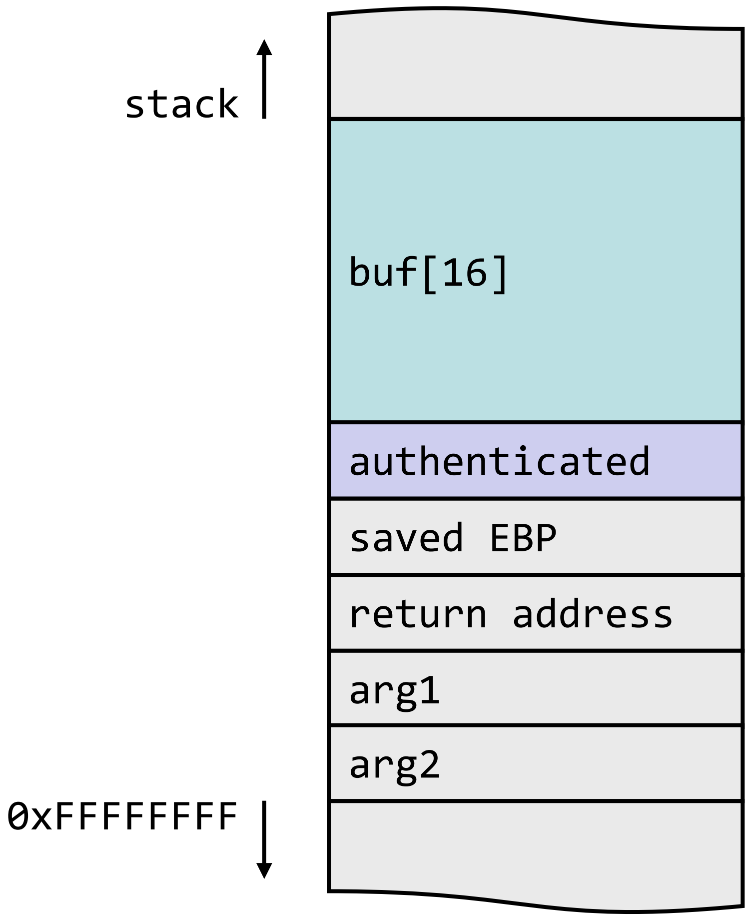
add user account

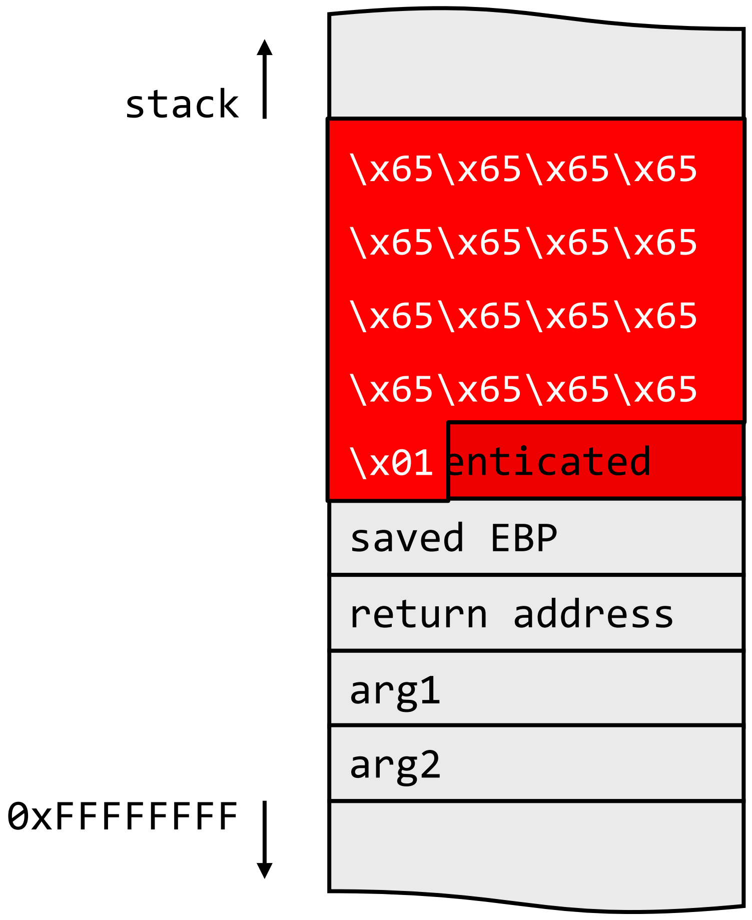
download and execute malware

(future lecture)

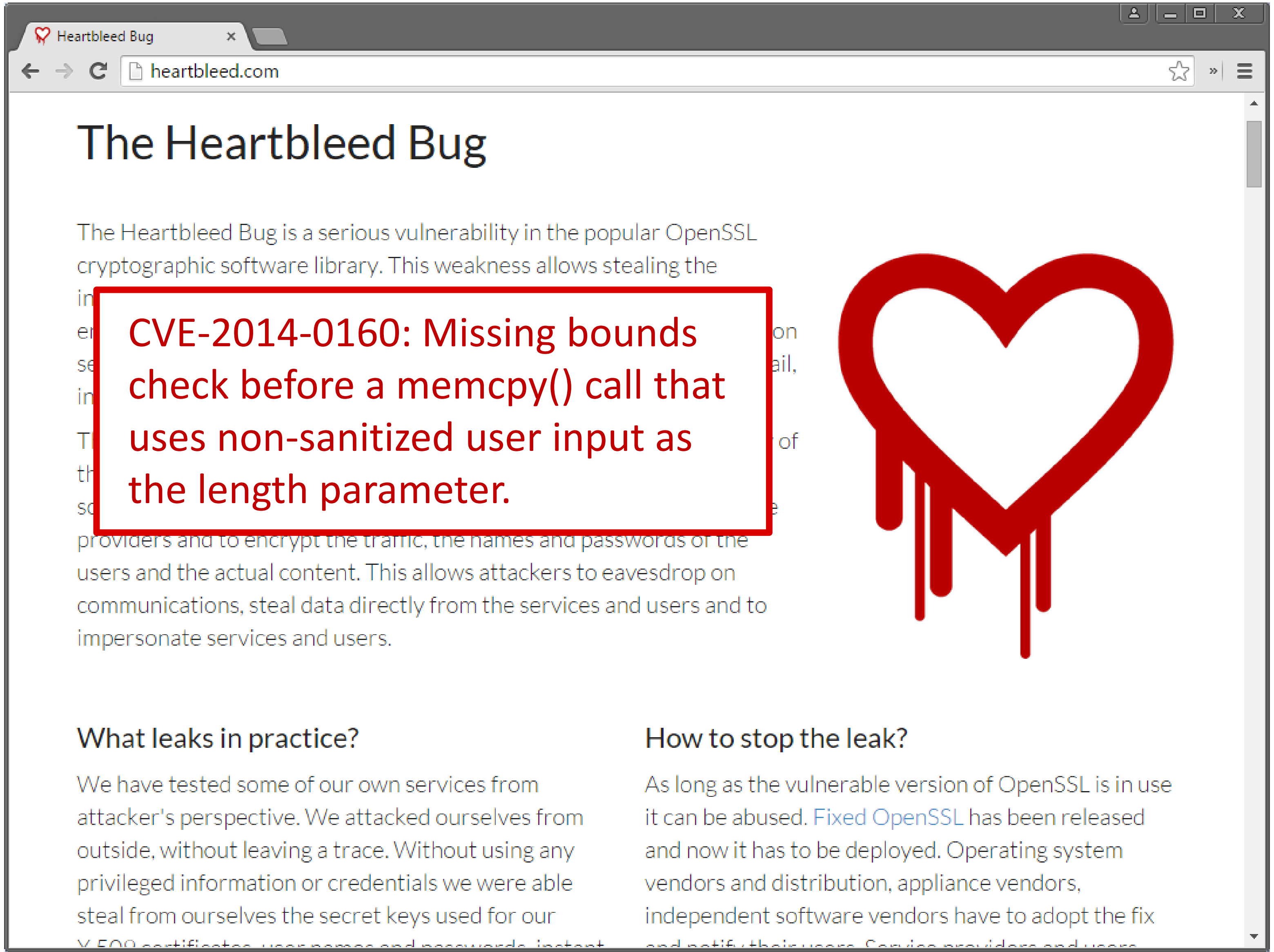
What can the attacker do? ***Overwrite program data***

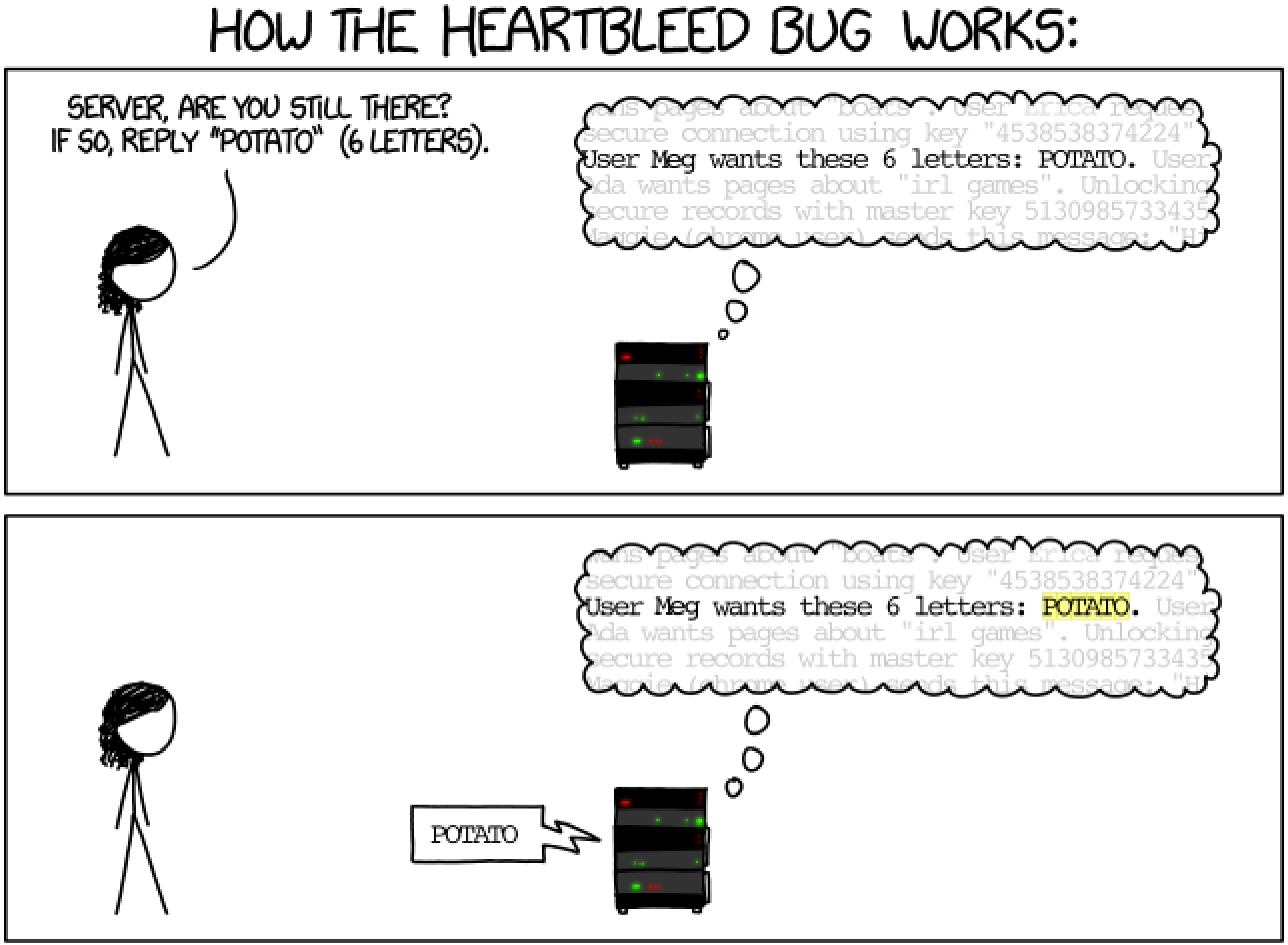
```
int main(int argc, char *argv[]) {
  int authenticated = 0;
  char password[16];
  gets(password);
  if (check_password(password) == TRUE) {
    authenticated = 1;
  }
  return authenticated;
}
$ ./authenticate AAAAAAAAAAAAAAAA && echo $?
0
$ ./authenticate AAAAAAAAAAAAAAAAA && echo $?
65
$ ./authenticate `printf "AAAAAAAAAAAAAAAA\x01"` && echo $?
1
```


stack
buf[16]
authenticated
saved EBP
return address
arg1
arg2
0xFFFFFFFF

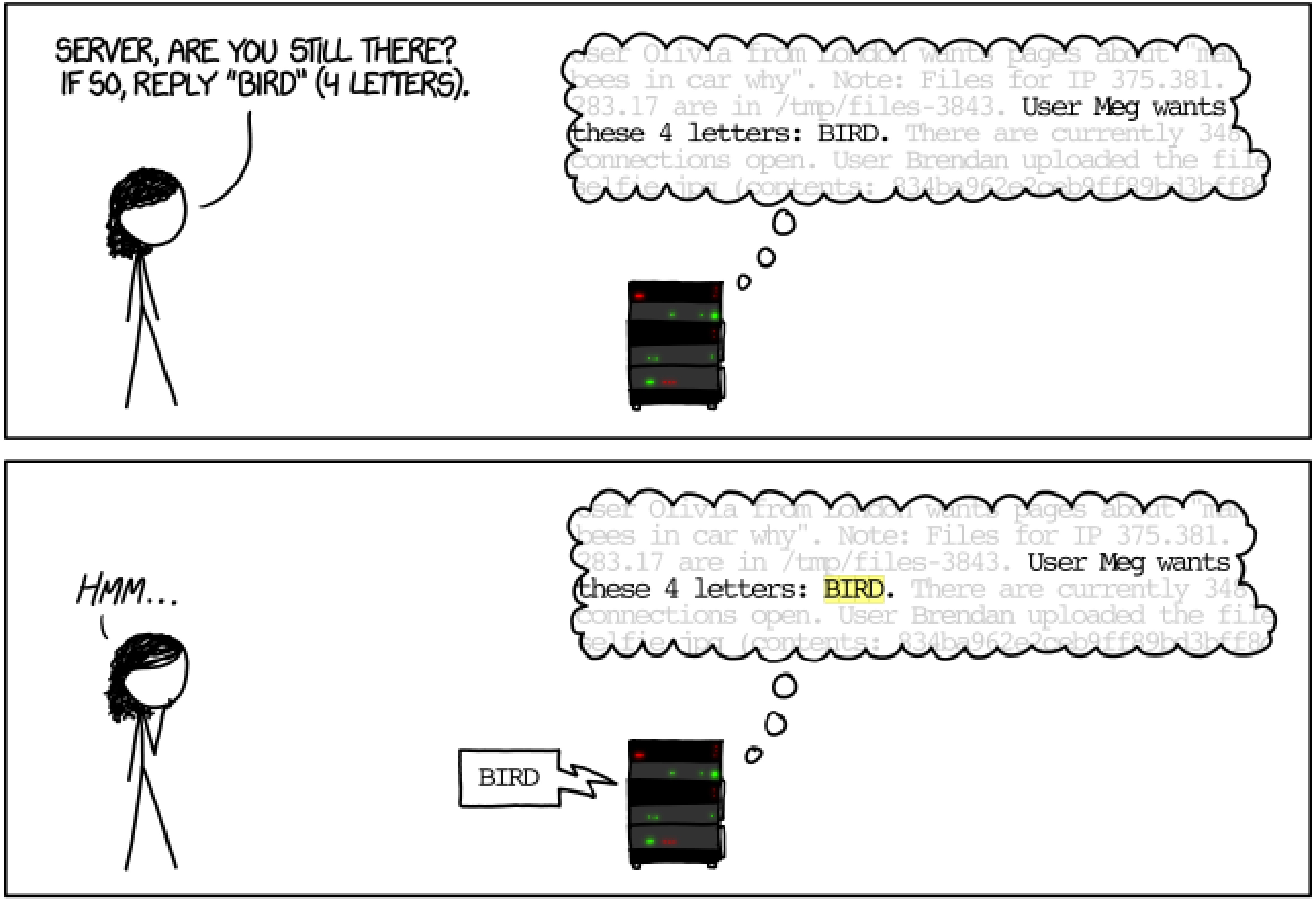

stack
\x65\x65\x65\x65
\x65\x65\x65\x65
\x65\x65\x65\x65
\x65\x65\x65\x65
\x01
enticated
saved EBP
return address
arg1
arg2
0xFFFFFFFF

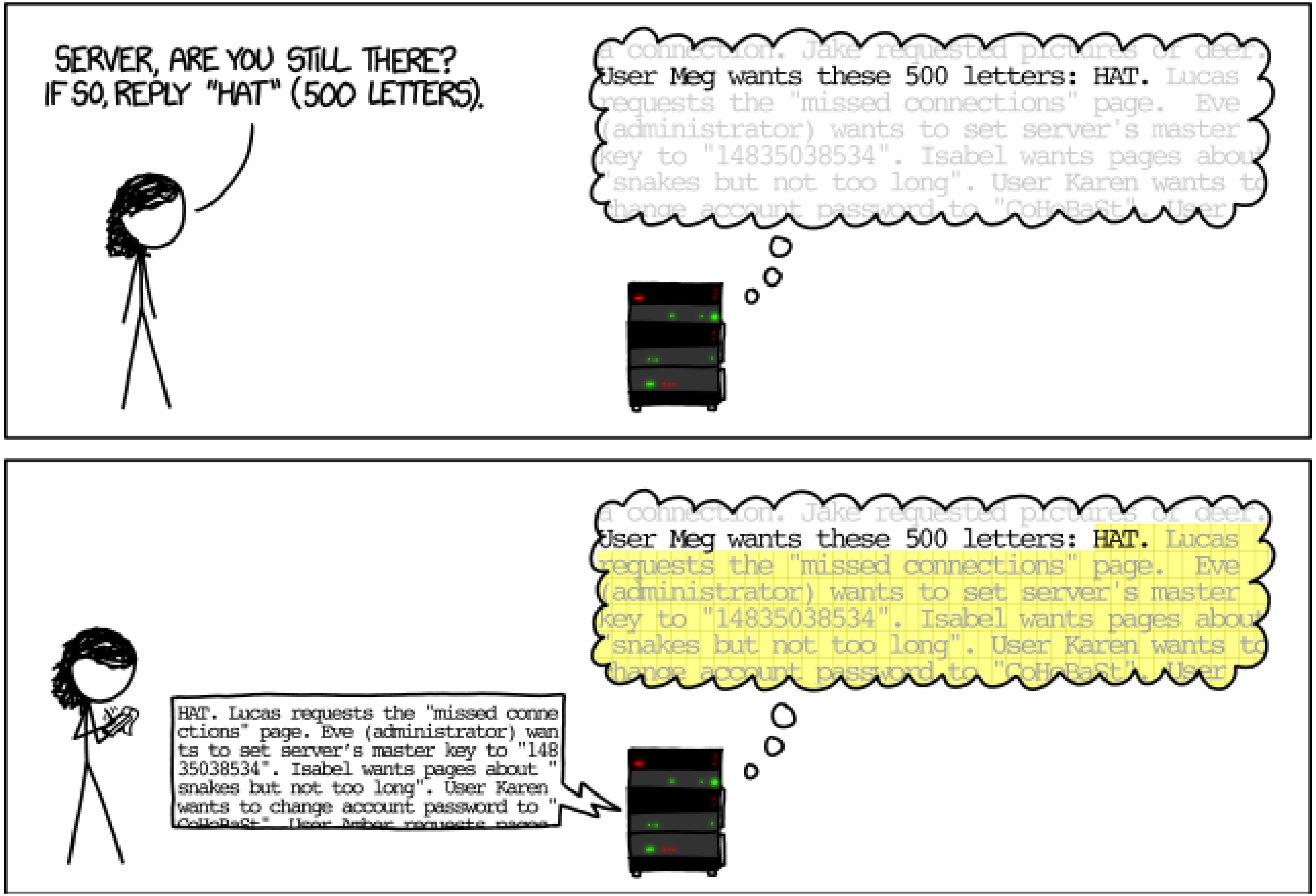
What can the attacker do? ***Leak data***





HOW THE HEARTBLEED BUG WORKS:
SERVER, ARE YOU STILL THERE? IF SO, REPLY "POTATO" (6 LETTERS).
secure connection using key "4538538374224"
User Meg wants these 6 letters: POTATO. User
da wants pages about "irl games". Unlocking
ecure records with master key 5130985733435
secure connection using key "4538538374224"
User Meg wants these 6 letters: POTATO. User
Ada wants pages about "irl games". Unlocking
secure records with master key 5130985733435
POTATO


SERVER, ARE YOU STILL THERE? IF SO, REPLY "BIRD" (4 LETTERS).
Olivia from London wants pages about
bees in car why". Note: Files for IP 375.381.
83.17 are in /tmp/files-3843. User Meg wants
these 4 letters: BIRD. There are currently
connections open. User Brendan uploaded the
HMM...
Olivia from London wants pages about
bees in car why". Note: Files for IP 375.381.
83.17 are in /tmp/files-3843. User Meg wants
these 4 letters: BIRD. There are currently
connections open. User Brendan uploaded the
BIRD


SERVER, ARE YOU STILL THERE? IF SO, REPLY "HAT" (500 LETTERS).
User Meg wants these 500 letters: HAT. Lucas
requests the "missed connections" page. Eve
(administrator) wants to set server's master
key to "14835038534". Isabel wants pages abou
"snakes but not too long". User Karen wants to
HAT. Lucas requests the "missed conne
ctions" page. Eve (administrator) wan
ts to set server's master key to "148
35038534". Isabel wants pages about "
snakes but not too long". User Karen
wants to change account password to "

Pointer manipulation

```
void vulnerable(void *arg, size_t len) {
  long val = 0;
  long *ptr = NULL;
  char buf[128];
  ...
  memcpy(buf, arg, len);
  *ptr = val;
  ...
}
```

*"Arbitrary write" capability: The attacker can write **controlled data** into a **controlled location***

Common Heap Errors

Initialization mistakes

`malloc()`, `realloc()` and C++ `new` do not initialize the allocated data.

Confusion between scalars and arrays

`new` and `delete` for scalars, `new[]` and `delete[]` for arrays

Failing to check return values

Functions like `malloc()` and `realloc()` return a NULL pointer when out of memory

Writing to already freed memory

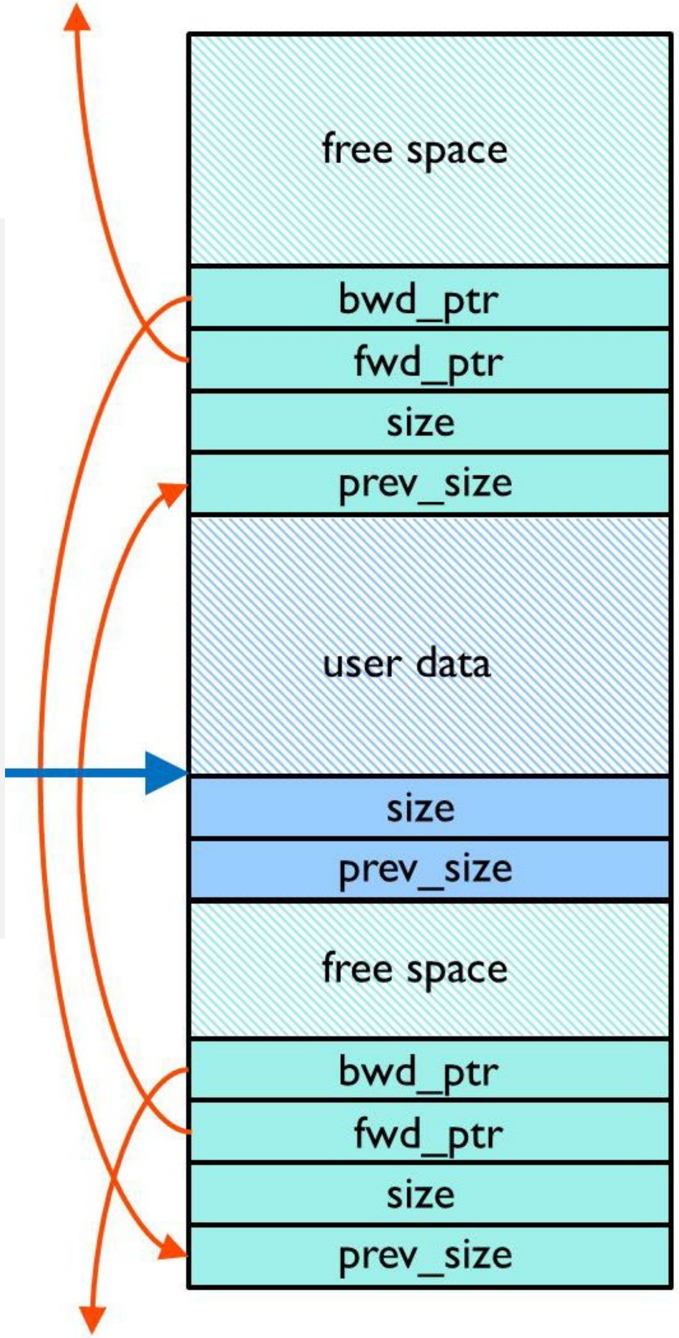
Freeing the same memory multiple times

Writing outside of the allocated area

Corruption of internal memory allocator data structures or allocated application data

Heap-based Overflows

```c
int main(int argc, char *argv[]) {
  char *p, *q;
  p = malloc(1024);
  q = malloc(1024);
  strcpy(p, argv[1]);
  free(q);
  free(p);
  return 0;
}
```



Arbitrary write when `free()` is called by carefully corrupting heap metadata

Format String Vulnerabilities

The `printf()` family of functions accept a format string denoting how a variable will be displayed

- `printf("%s", str)` → prints `str` variable as string
- `printf("%d", num)` → prints num as a decimal value
- `printf("%x", num)` → prints num as a hexadecimal value

Format strings can also *write* to memory

- `printf("ABCD%n", &i)` → write the number of bytes output so far to the memory address of the second argument

What if…

- The programmer does not supply a format string?
- Fewer arguments are passed than the number of format string parameters?

Simple format string error example

```
int main(int argc, char *argv[]) {
  printf("Input: ");
  printf(argv[1]);
  printf("\n");
}

$ ./fmt test
Input: test

$ ./fmt "%08x %08x %08x %08x"
input: b773c080 0804846b b7721ff4 08048460

$ ./fmt $(printf "\x18\xa0\x04\x08")%x%x%x%x%n
```

Safer way

```
int main(int argc, char *argv[]) {
  printf("Input: ");
  printf("%s", argv[1]);
  printf("\n");
}
```

Other Memory-related Exploitable Conditions

NULL-termination errors

Dangling pointers

NULL pointer dereferences

String truncation

Single-byte overwrite

Off-by-one accesses

Double free

…

Race Conditions

Situations in which the behavior of the program depends on the timing of some event

Critical section

- Opens up a window of opportunity for the attacker

Race conditions occur in many different contexts

- Multi-threaded programs with different threads operating on the same data
- Distributed applications that perform multi-step transactions
- Time of check to time of use (TOCTTOU): changes may happen between *checking* a condition and *using* the results of the check

Filesystem race condition example

```
// setuid program

if (access("file01", W_OK) != 0) {  // access() checks the real uid (not eid)
    exit(1);
}
                                  ln /etc/password file01

fd = open("file01", O_WRONLY);
write(fd, buffer, sizeof(buffer));  // write() modifies /etc/passwd
```

iOS 8.1 Hardware-assisted Screenlock Bruteforce

Successfully brute-force device PIN *even if "wipe out after 10 failed attempts" is enabled (!)*

Vulnerable code:

1. Display "incorrect pin" message

Power off the device

2. `++attempts;`

Correct code:

1. `++attempts;      // gets written to flash memory`
2. Display "incorrect pin" message


No!
Ssh!
Almost...
OK, I'm listening
Pwn3d :)
1234

Program Logic Flaws

Flaws in the design itself, or in the way the design was implemented in the program code

- Rather than lower-level bugs (overflows etc.)

Indicative examples

- Abuse of functionality (e.g., lock another user out with repeated failed attempts)
- Workflow circumvention (e.g., skip payment info and jump straight to delivery info)
- Information leakage (e.g., through hidden form fields)
- Insufficient/poor validation (e.g., negative number of items)

Diverse and complicated ➔ very difficult to find

GOTO FAIL

iOS 7.0.6 signature verification error

Legitimate-looking TLS certificates with mismatched private keys were unconditionally accepted…

```
if ((err = SSLHashSHA1.update(&hashCtx, &serverRandom)) != 0)
        goto fail;
if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
        goto fail;
        goto fail;      ?!!?!?!?
if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
        goto fail;
...
                                  Check never executed
fail:
    SSLFreeBuffer(&signedHashes);
    SSLFreeBuffer(&hashCtx);
    return err;         Return with err == 0
```